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Topography effects in the polarization of earthquake signals: a comparison between surface and deep recordings

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ABSTRACT Local and regional earthquakes recorded in 2007 by two seismic arrays at Gran Sasso (Italy), one located at surface and one at 1.4 km depth, have been analyzed. Polarization properties of the seismic wavefield have been estimated at both arrays on a short sliding window and in several frequency bands. Array methods were also applied, and the estimated slowness and backazimuth were used to compute the stacking of phase shifted signals in order to improve the signal to noise ratio. Results of polarization computed over single station and array stacked signals have been compared between the two arrays. A well defined polarization azimuth, roughly perpendicular to the main massif ridges, is evident at surface in a broad frequency band. This is observed for earthquake body waves and coda waves. On the contrary, underground the same effect is slightly visible only at very low frequency.

Key words: topography, earthquakes, Gran Sasso, central Italy.

1. Introduction

The amplitude and polarization of seismic signals recorded at surface may be strongly affected by the propagation of the incident wave throughout the uppermost Earth structure. It is well known that soil-rock layering with strong velocity contrast can significantly influence the spectral content, amplitude and duration of seismic motion. In addition, more recent studies have evidenced as topography, filled basin and fault zone are sources of local effects through the different amplification of ground motion in a direction compared with others. Site effects are of interest because ground shaking amplification in case of earthquakes can be responsible of damage greater than expected.

A typical effect of a soil-rock layered structure characterized by a large impedance contrast is the amplification of ground motion and the high ratio between horizontal and vertical amplitude (H/V) observed at a well defined frequency (Kramer, 1996). The ground motion amplification at crest compared with foothill recording is another well known phenomenon observed in many places and described in many papers (Bard and Tucker, 1985; Geli *et al*., 1988; Chavez-Garcia *et al*., 1996; Cultrera *et al*., 2003; Massa *et al*., 2010; Pischiutta *et al*., 2010). More recent studies investigate the dependence of site effects by lateral heterogeneity and highly fractured rock. Strong lateral heterogeneity may be found upon landslides (Del Gaudio *et al*., 2008), while highly fractured rocks are very common at the two sides of faults (Martino *et al*., 2006; Marzorati *et al*., 2011). While a soil-rock flat layered structure produces a generally well understood soil type transfer function and H/V spectral ratio (Albarello and Lunedei, 2010), the site effects produced by topography, landslide bodies, and faults proximity are much more difficult to interpret. With regard to the topography, theoretical models have been developed and used to compute synthetic signals, taking into account the polarization (P, SV, SH) and the incidence angle of the incident body wave (Pedersen *et al*., 1994). Geli *et al*. (1988), comparing observations and theoretical models, inferred that seismic amplitude is amplified at crests and is de-amplified at valley or bottom of hill. The frequency at which the amplification occurs corresponds to wavelengths comparable with the mountain widths, and observed results are in good agreement with the expected ones. However, often the observed amplification is much greater than the predicted value, as pointed out by many authors (Geli *et al*., 1988; Chavez-Garcia *et al*., 1996). Some experiments that involved the use of local earthquakes and seismic noise were carried out to compare theoretical amplification factors with H/V spectral ratios and standard spectral ratios with respect to a reference site, but no uniform results about all the used techniques have been evidenced (Chavez-Garcia *et al*., 1996). Many experimental studies observe that maximum amplification is roughly related to the "sharpness" of the topography and amplification at mountain top is generally larger on horizontal components and for S waves. Topographic complexity, such as the presence of neighbouring ridges, can be responsible for large crest-base amplification and also for directional effects on the polarization of seismic waves (Pischiutta *et al*., 2010). Buech *et al*. (2010) highlighted the topographic amplification effect on a small elongated bedrock-dominated hill and linked the observed dilation and degradation of rock-mass to the amplification effect of seismic waves on the ridge. Moreover, the amplification of seismic waves due to topographic irregularities was also evidenced through numerical and analytical approaches applied to real cases (Paolucci, 2002). In this last work, the author compared the numerical results between 2D and 3D approaches and discussed the results in the framework of Eurocode 8 rules for topographic amplification factors. On the other hand, often the comparison of observed seismograms with synthetic signals did not give satisfying results, indicating that the observed site effects cannot be attributed to the topography only. Therefore other possible causes have been considered, such as the presence of unconsolidated rock of variable thickness [like landslides: Del Gaudio *et al*. (2008)], and the proximity of faults (Cultrera *et al*., 2003; Di Giulio *et al*., 2009).

In the last years topographic amplification has roused great interest among scientists due to the possibility to trigger failure of rock slopes and to induce catastrophic seismically induced landslides, and many efforts have been made to link the topography slope to the local site amplification factors (Wald and Allen, 2007). Empirical methods applied in most of the studies have shown that amplification at the top of a crest with respect to the base is observed at a resonance frequency, given the mountain shape and size. In addition, the amplification if often observed in the direction perpendicular to the elongation of the edifice and amplified ground motion can be related also to the presence of weathered rock mass or the proximity of a faults.

In this paper we describe the results of polarization analysis performed on earthquakes recorded at Gran Sasso (central Italy), compare the polarization of surface and underground recordings, and discuss its relation with the mountain topography. The analyzed earthquakes were recorded by a temporary array, named Fontari (FON), installed in 2007 on Mt. Gran Sasso, and by the permanent array Underseis (UND), installed at 1.4 km depth in the same area.

2. Data set

FON array was installed at surface on Mt. Gran Sasso, in the area of Campo Imperatore. Composed by six stations equipped with Lennartz LE3D lite, 1 Hz three component seismometers, it was operating for about six months in 2007 (Fig. 1). The aperture of the array was about 600 m (Fig. 2). UND array is operating inside the Gran Sasso Physics Laboratory since 2003 (Scarpa *et al*., 2004; Saccorotti *et al*., 2006). It consists of 20 short-period MARK L4C-3D, 1 Hz three component seismometers. UND array is suitable for a detailed monitoring of local seismicity, being characterized by low background seismic noise. The horizontal distance between FON and UND arrays is about 1.5 km, while the elevation difference is about 1 km (Fig. 1).

Many local and regional earthquakes were recorded by the two arrays. The 35 events characterized by the best SNR were selected for this work (Fig. 3). The location of local earthquakes was taken from the ISIDE catalogue (http://iside.rm.ingv.it/iside/standard), while the epicenters of regional events come from the EMSC catalogue (http://www.emsc-csem.org). Selected earthquakes have magnitude in the range 1.7 – 4.0 and 3.5 – 5.4 for local and regional events, respectively. The farthest analyzed earthquakes were locate in Greece, at distance up to 860 km. An example of local earthquake recorded at one station of each array is shown in Fig. 4. Several analyses were applied to these earthquakes aimed at a detailed study of the seismic wavefield.

3. Method

Detailed analyses were applied to seismic noise and earthquake signals. In this paper, we focus our attention on the polarization analysis of earthquakes. It was performed by the covariance matrix method in time domain (Montalbetti and Kanasevich, 1970; Jurkevics, 1988). The covariance matrix for a N samples window is defined as

$$S_{ij} = \frac{1}{N}\sum_{k=1}^{N} A_i^k A_j^k \tag{1}$$

where A_i^k is the amplitude of the k-th sample of the i-th seismogram, and i takes three values corresponding to the three components of ground velocity. S_{ij} has three real eigenvalues $\lambda_1 \geq \lambda_2 \geq \lambda_3$, used to compute the rectilinearity RL of the particle velocity through the equation

$$RL = 1 - \frac{\lambda_2 + \lambda_3}{2\lambda_1}. \tag{2}$$

The polarization direction of the particle motion is given by the eigenvector of the covariance

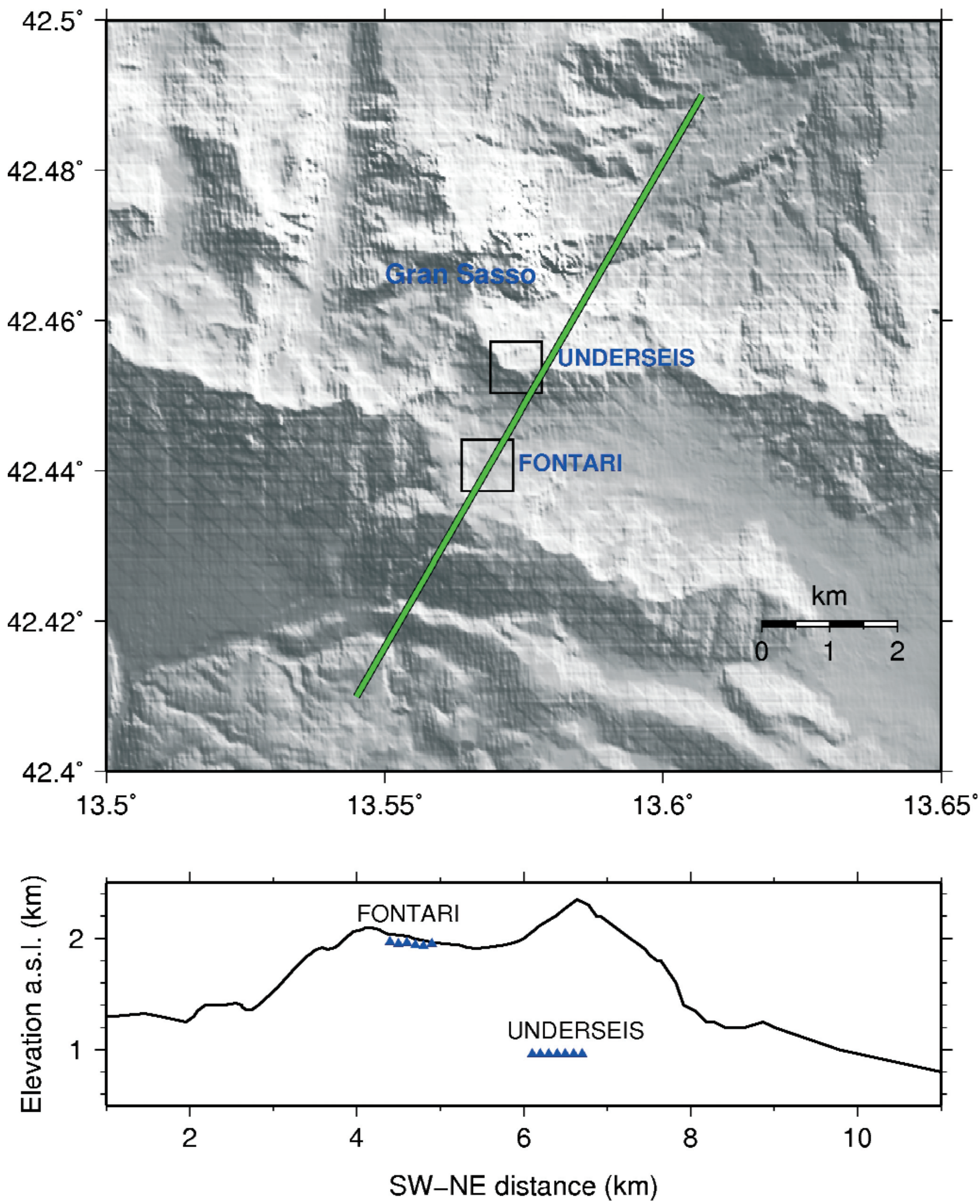

Fig. 1 - Top: topography of the Gran Sasso massif with the position of the surface array FON and the underground array (UND). Bottom: cross-section of Mt. Gran Sasso along the NE-SW profile shown in the map above.

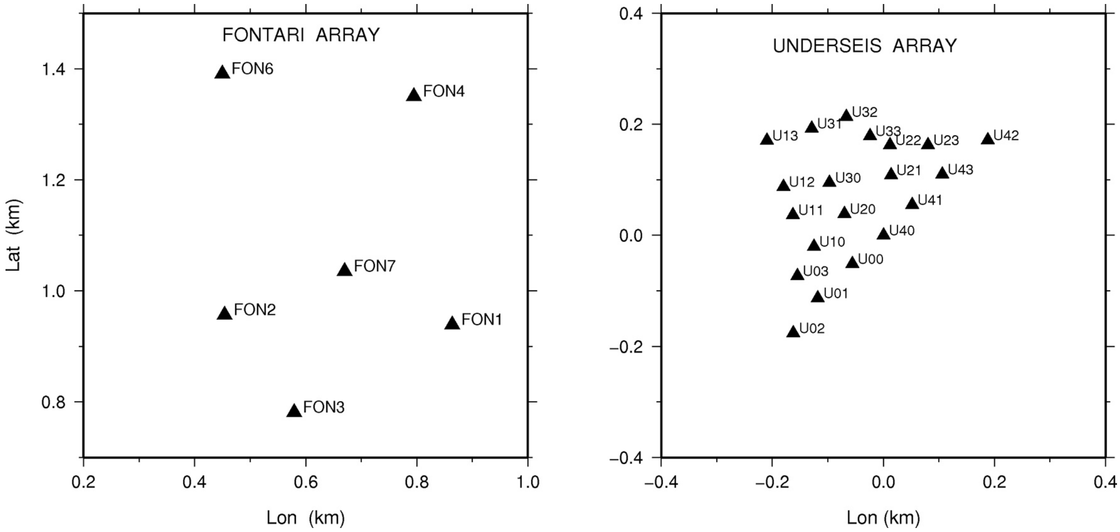

Fig. 2 - Configuration of the two arrays FON and UND. Some of the 20 stations located underground (UND) have not been used in our analysis because not operating or affected by local sources of noise.

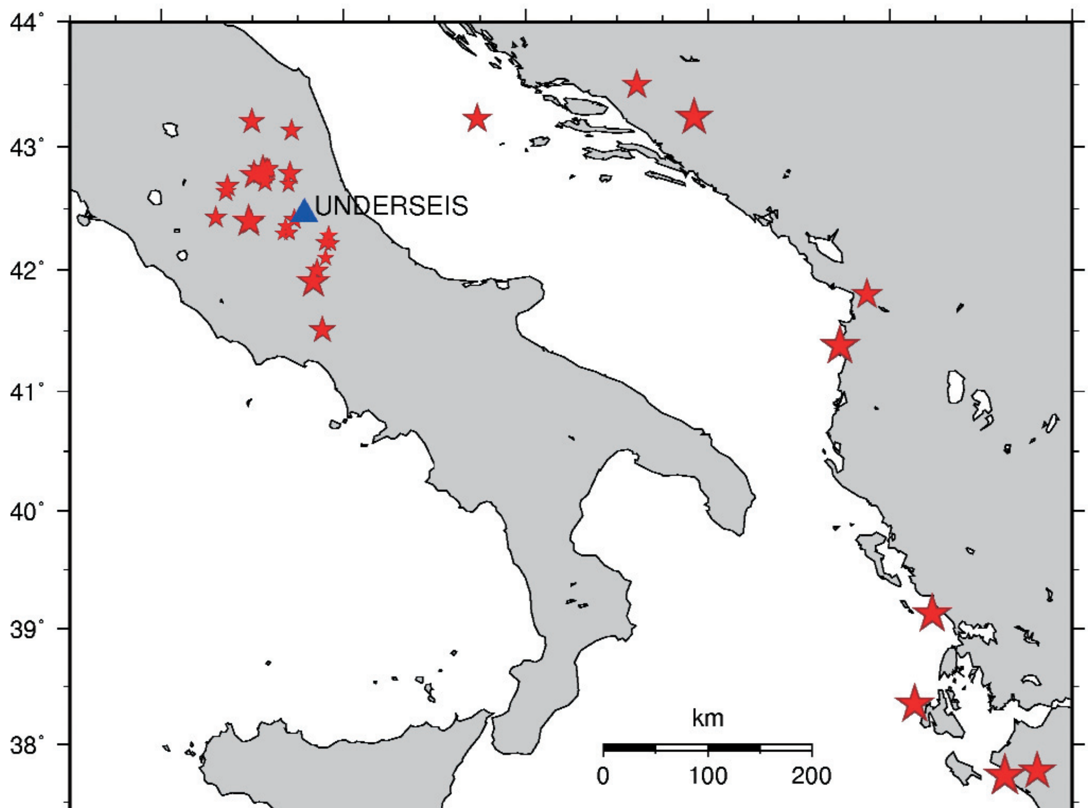

Fig. 3 - Epicenters of the 35 local and regional earthquakes analyzed in this work.

matrix associated with the eigenvalue λ_1. The angle β between polarization direction and vertical axis is called "polarization incidence". The "polarization azimuth" is defined as the angle between the north and the projection of the polarization vector on the horizontal plane.

When an array of three component stations is available, polarization analysis may benefit of more information, and hence it may yield more reliable results. The first use of array data is a stacking of the signals over the array stations to improve the signal to noise ratio (SNR). Another improvement comes from the results of array analysis, which furnish the propagation direction and apparent velocity of coherent signals. This information is important to estimate the 3D wave vector, given a velocity model. Once the wave vector of the coherent signal has been estimated, we can compute the angle γ between polarization direction and wave vector, which is useful to distinguish between P and S waves (La Rocca *et al*., 2001, 2010).

To estimate propagation parameters (apparent velocity and azimuth) of the coherent signals we applied two array methods: Beam Forming (BF) in frequency domain (Capon, 1969; Rost and Thomas, 2002), and Zero Lag Cross Correlation (ZLCC) in time domain (Del Pezzo *et al*., 1997). Results of array analysis, combined with polarization parameters, give the most exhaustive picture of the seismic wavefield. We used the estimated propagation parameters to compute the array stacked polarization analysis, that is the polarization of signals stacked after a phase shift. This procedure improves the SNR, and it is particularly useful in the analysis of coda waves.

Array and polarization analysis were performed in a short-duration time windows, sliding along the seismogram starting at the P-wave onset. We performed the analysis in the following frequency bands: 1 - 2 Hz, 1 – 3 Hz, 2 – 4 Hz, 3 – 6 Hz, 4 – 8 Hz, 6 – 12 Hz. The window length was smaller for the higher frequency windows, in order to contain only about three periods at the central frequency. Moreover, the window length was different between the ZLCC and BF methods, since the latter requires a number of samples equal to a power of 2, being a spectral technique. For this reason results of the two methods may be slightly different. Since there is no reason to prefer one method to the other, we present both results.

A statistical analysis was applied to the parameters estimated by the polarization analysis. The distributions of polarization azimuth were computed at both arrays and compared each other for all analyzed earthquakes and for any frequency band. The distributions were computed separately for body waves (P, P coda and S waves) and coda waves. Coda waves are characterized by a random distribution of propagation direction, therefore the polarization should not be affected by this parameter. This is the reason to keep separate body waves and coda waves in the statistical analysis of polarization parameters. The coda beginning was estimated as two times the shear-wave travel time, while the coda end was estimated as the time at which the rms is 1.5 times the value of seismic noise. The results of polarization analysis were selected applying an appropriate threshold of coherence for BF method and correlation for ZLCC method.

4. Results

The comparison of the seismic signals recorded at surface and underground shows some significant differences. Seismic signals have smaller amplitude at depth (Fig. 4), where the surface amplification is negligible for frequency greater than 2 Hz. This is observed for both seismic noise and earthquakes. Moreover, signals recorded underground are more similar among

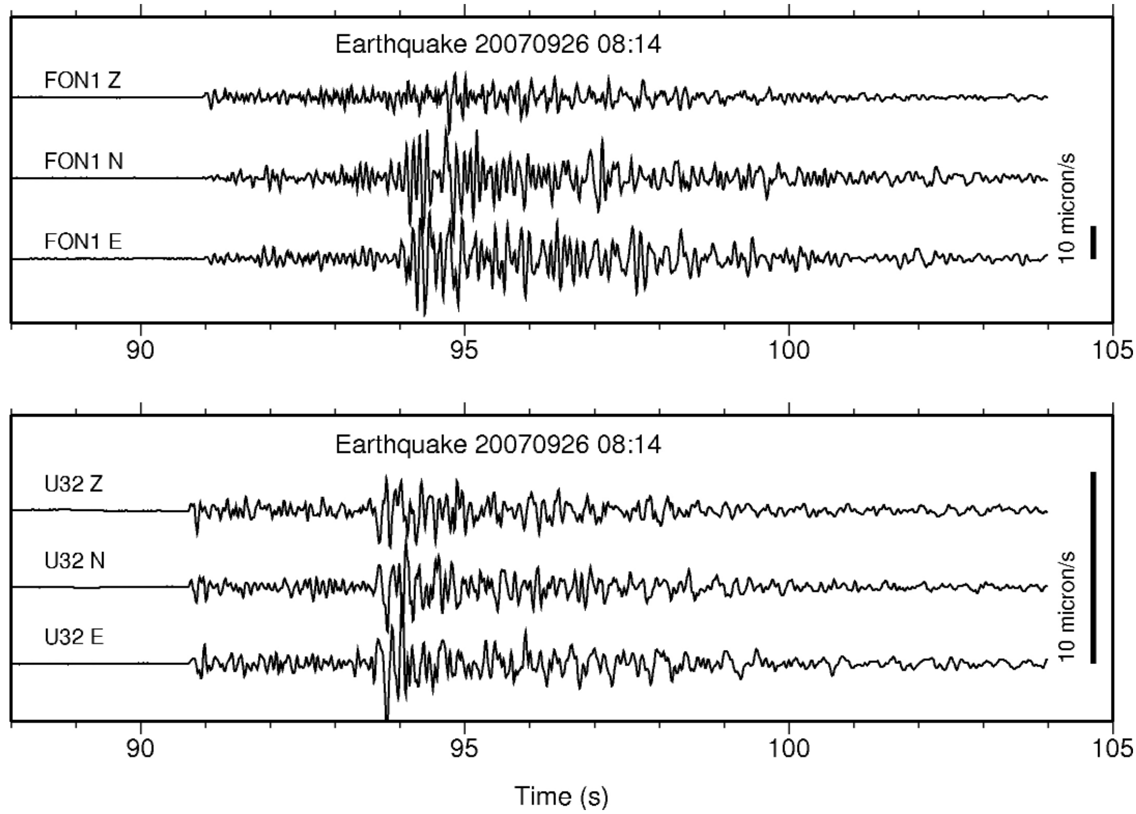

Fig. 4 - Seismograms of a local earthquake recorded at surface (FON1, top plot) and underground (U32, bottom plot). The most striking difference between the two sites is the much higher amplitude of the signals recorded at surface.

the array stations compared with the surface recordings. This is due to the much more uniform site response at depth and the shorter distances among the underground stations, while at surface the seismic noise and site effects are more variable among the array stations, and distances are longer. At both arrays the seismic signals show high similarity among the array stations for the earthquake onset, where the correlation (or coherence) is very high. The backazimuth estimated at both surface and underground arrays for direct P waves is consistent with that calculated from the source-array direction.

The normalized distributions of polarization azimuth computed from the stacked waveforms at FON array in three frequency bands, 1-2 Hz, 1-3 Hz and 2-4 Hz, are shown in Fig. 5. For each frequency two plots show the results obtained after the phase shift computed by BF and ZLCC methods. These distributions contain the results selected for the earthquake coda of all events by applying an appropriate threshold of coherence (for the BF method) or correlation (for the ZLCC method). Therefore, they are representative of the most coherent phases in the coda waves. The six distributions are strongly anisotropic, with two large peaks centred at 50 and 230 degrees, corresponding to the NE and SW directions, respectively. Fig. 6 shows the distributions of polarization azimuth computed for the same earthquakes, in the same frequency bands, recorded

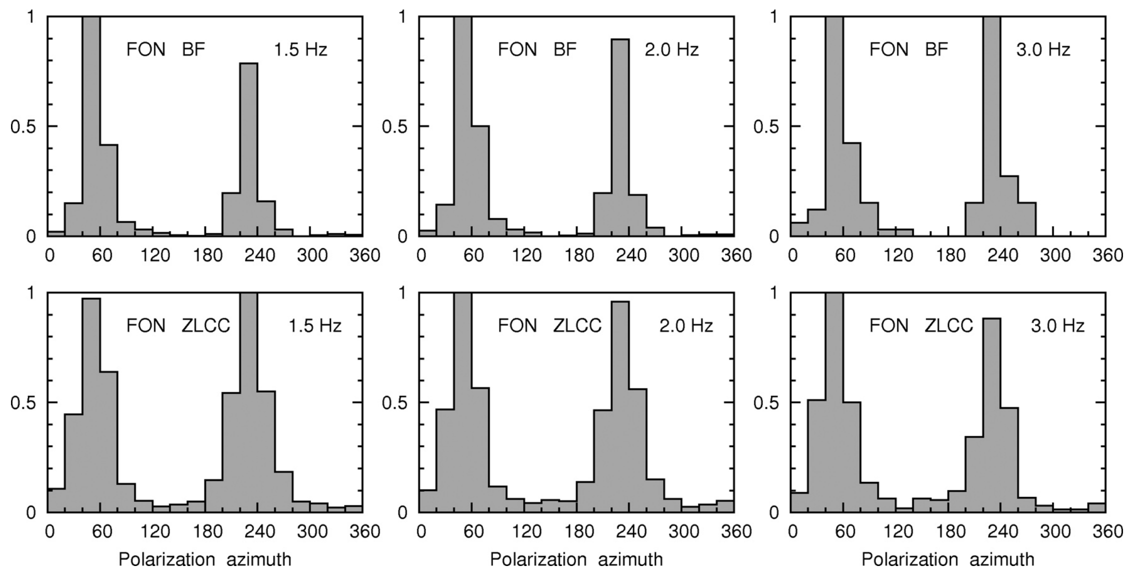

Fig. 5 - Normalized distributions of the polarization azimuth computed over array stacked signals after the phase shift obtained by BF (top) and ZLCC (bottom) methods at FON array. These results refer to the coda waves of all analyzed earthquakes at 1.5 Hz, 2 Hz and 3 Hz central frequencies.

at UND array. At UND the distributions are more uniform and the two peaks seen at FON disappear. The distributions of polarization azimuth have been computed also for higher frequencies, and results are similar to those shown in Figs. 5 and 6, although the lower number of coherent phases found at FON array makes them less statistically important. The same statistical analysis performed on selected body waves gives very similar results, not shown here for shortness.

Polarization analysis was applied also to single station data for any earthquakes. The distributions of polarization azimuth were then stacked over all earthquakes for any stations of each array, as shown in Fig. 7 for the central frequency 3 Hz. At surface a predominant NE-SW direction is again evident for all stations, while underground the most of distributions are quite isotropic. Since a preferred polarization direction is not seen at depth, it must be produced in the shallowest part of the propagation path, that is by the interaction of the seismic wavefield with the free surface and/or by other site effects.

The non-uniform distribution of polarization azimuth indicates that the amplitude of ground motion is anisotropic, that is greater in the polarization azimuth direction and smaller in the orthogonal direction. This kind of ground amplification is observed very often at sites where the topography is significantly different from being flat. Therefore, we believe that the preferred polarization direction is mainly a topography effect caused by the mountain shape, which is elongated in the NW-SE direction (Fig. 1). To estimate the difference of the signal amplitude in the two directions radial and transverse with respect to the mountain reliefs, we rotated the horizontal components into radial (315 degrees) and transverse (45 degrees, the maximum of polarization azimuth distributions) components. Spectra of radial and transverse components

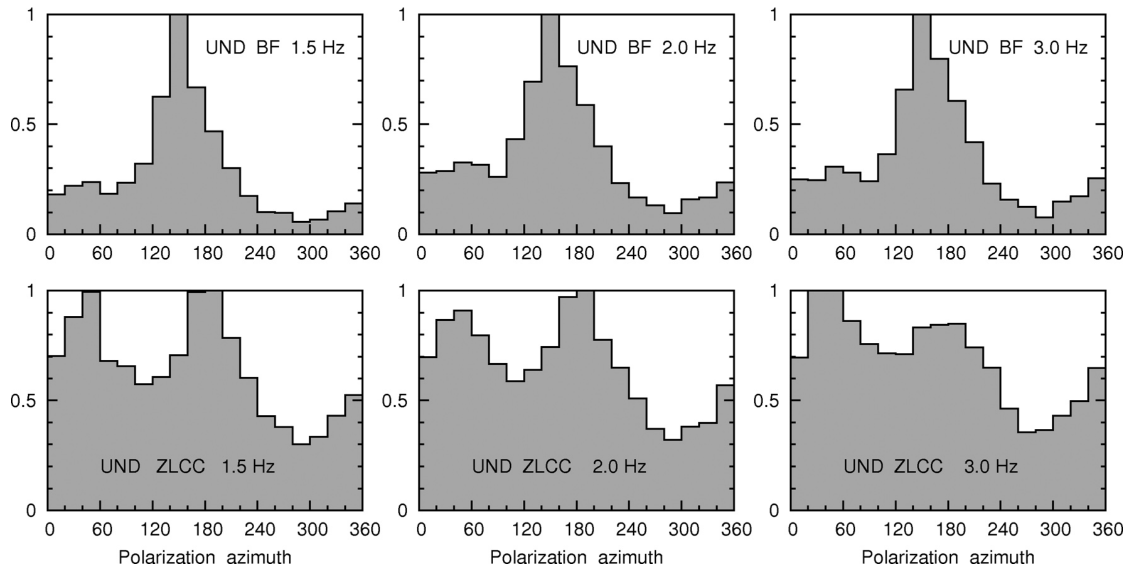

Fig. 6 - Normalized distributions of the polarization azimuth computed over array stacked signals after the phase shift obtained by BF (top) and ZLCC (bottom) methods at UND array. These results refer to the coda waves of all analyzed earthquakes at 1.5 Hz, 2 Hz and 3 Hz central frequencies.

were computed for each earthquake at all stations of the two arrays. Then, we stacked the transverse spectra and radial spectra at each array, and computed the spectral ratio between the average T-spectrum and the average R-spectrum. The spectral ratio gives a precise estimate of the relative amplitude between transverse and radial components as a function of frequency. Fig. 9 shows the spectral ratio for 10 regional earthquakes recorded at the two arrays, and the spectral ratio computed for the P coda of a teleseism. The difference between surface and underground results is evident in these spectral ratios. At surface the spectral ratios are all significantly greater than 1 in the frequency range 1-5 Hz, with average value near 1.5. On the contrary, the spectral ratios estimated underground do not show significant variations with frequency, and their average value is near 1, as expected. Assuming a shear wave velocity of 3 km/s, the frequency range 2-5 Hz corresponds to wavelength in the range 0.6-1.5 km. Therefore, the topographic amplification effect in this frequency range is reasonably produced by the mountain ridge located SW of FON array, that has a spatial width of about 1 km (Fig. 1). In the frequency range 1-2 Hz, the corresponding S wavelength is 1.5-3 km. This wavelength range cannot be directly associated with the size of the two high crests and the width of the entire mountain, which is roughly 5 km (Fig. 1). An S wave of wavelength 5 km (the width of Mt. Gran Sasso measured at 1.5 km a.s.l.), would have frequency in the range 0.6 – 0.65 Hz. Therefore, we expect a transverse amplification produced by the entire mountain in this frequency range. To check this hypothesis we analyzed the P coda of a strong teleseism (*M* 8.4, Sumatra). These signals have a good SNR in the frequency range 0.5-1 Hz, and are characterized by near vertical incidence due to the extremely far epicenter. The spectral ratio computed at the surface array shows a peak of amplitude greater than 3 at about 0.7 Hz (bottom plot of Fig. 9). At the same frequency a maximum is found also

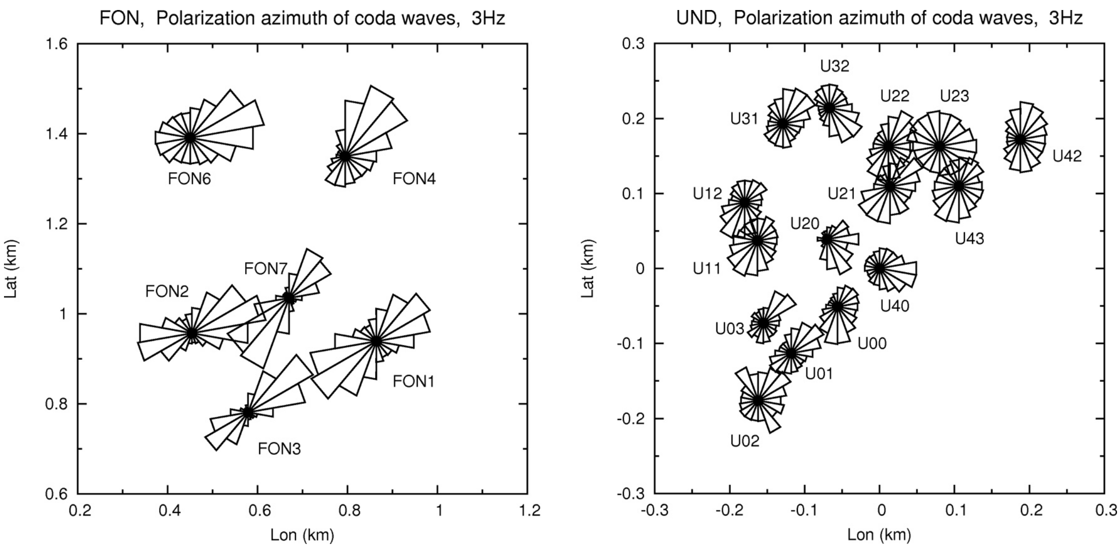

Fig. 7 - Distributions of polarization azimuth of coda waves (average among all earthquakes) computed for any stations of the two arrays at the central frequency of 3 Hz. At FON array a predominant NE-SW direction is seen at all stations.

at the underground array, although its amplitude is much smaller than that of FON array.

5. Discussion and conclusion

Results of our analysis indicate that the polarization of seismic signals recorded at surface on Mt. Gran Sasso, in the area of Campo Imperatore is characterized by a well defined NE-SW polarization direction. Gran Sasso massif is elongated NW-SE, and also the minor ridge near the array has the same direction. The observed polarization direction is roughly perpendicular to the ridge direction in a wide frequency range. This polarization is evident from single station data and from array stacked signals. The estimated wavelengths of shear wave fit well the width of the near ridge south of the array at high frequency (2-5 Hz) and the width of the entire mountain at lower frequency (0.6-0.7 Hz). Therefore, we attribute the observed polarization effect mainly to the interaction of the incident wavefield with the topography.

The use of array data allows the estimation of propagation parameters (apparent velocity and backazimuth) that have been used to compute the stacking of phase shifted signals. This procedure improves the SNR of coherent signals by reducing the contribute of incoherent noise, yielding an estimation of polarization parameters averaged among the array sites. This is particularly important at surface, where local geology may be significantly different at short distances with effects on the polarization of high frequency seismic signals recorded by single stations. In our work we took further advantage from the analysis of the same earthquakes recorded by another array installed at 1.4 km depth. The comparison of results from the two arrays demonstrates that the most important polarization features of the coherent wavefield are produced by the interaction with the free surface. The morphology of Gran Sasso massif,

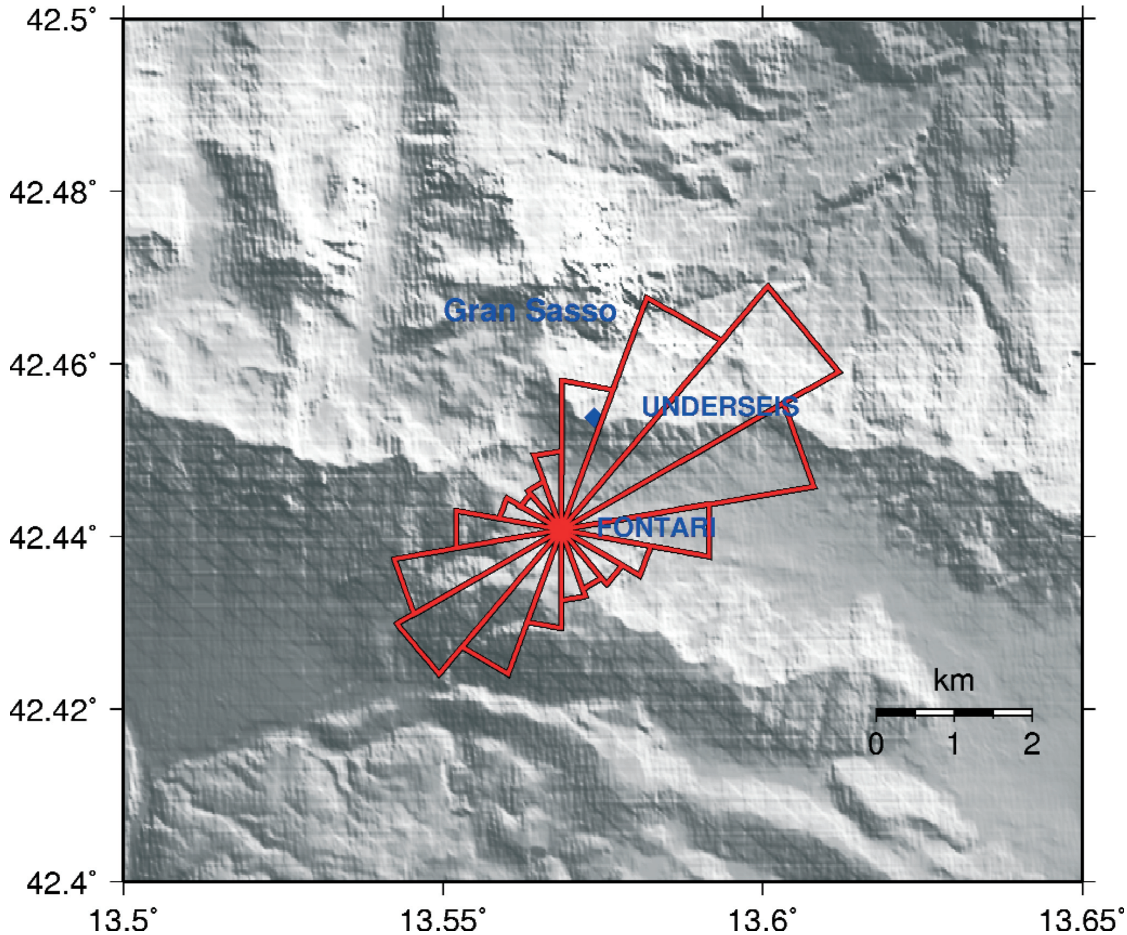

Fig. 8 - Polarization azimuth distribution of coda waves at FON array averaged among all stations and all earthquakes. Topography of the Gran Sasso is shown in background by shaded gray color.

elongated NW-SE with an average width of about 5 km (Fig. 1), is complex, with the presence of many ridges and smaller scale geological irregularities. The sites of FON array stations are characterized by the presence of loose material, mostly produced by the action of ice during the winter season, and by old landslide deposits. The thickness of such unconsolidated rocks is variable at the different stations, and probably it is the cause of local signal amplification observed at some stations compared with the average array amplitude. Discriminating between effects produced by the local geology and effects produced by the topography is not easy, and it is a debated topic. Many authors have studied the effects of topography on the polarization of the seismic signals, and found good agreement between observed and theoretical results in many cases (Paolucci, 2002; Buech *et al*., 2010). On the other hand, more recent studies have been focused on the investigation of the effects produced by highly fractured rock nearby the seismic station. For example, Di Giulio *et al*. (2009) describe quickly changing polarization properties of the seismic noise depending on the distance from known local faults at Etna volcano. Similar

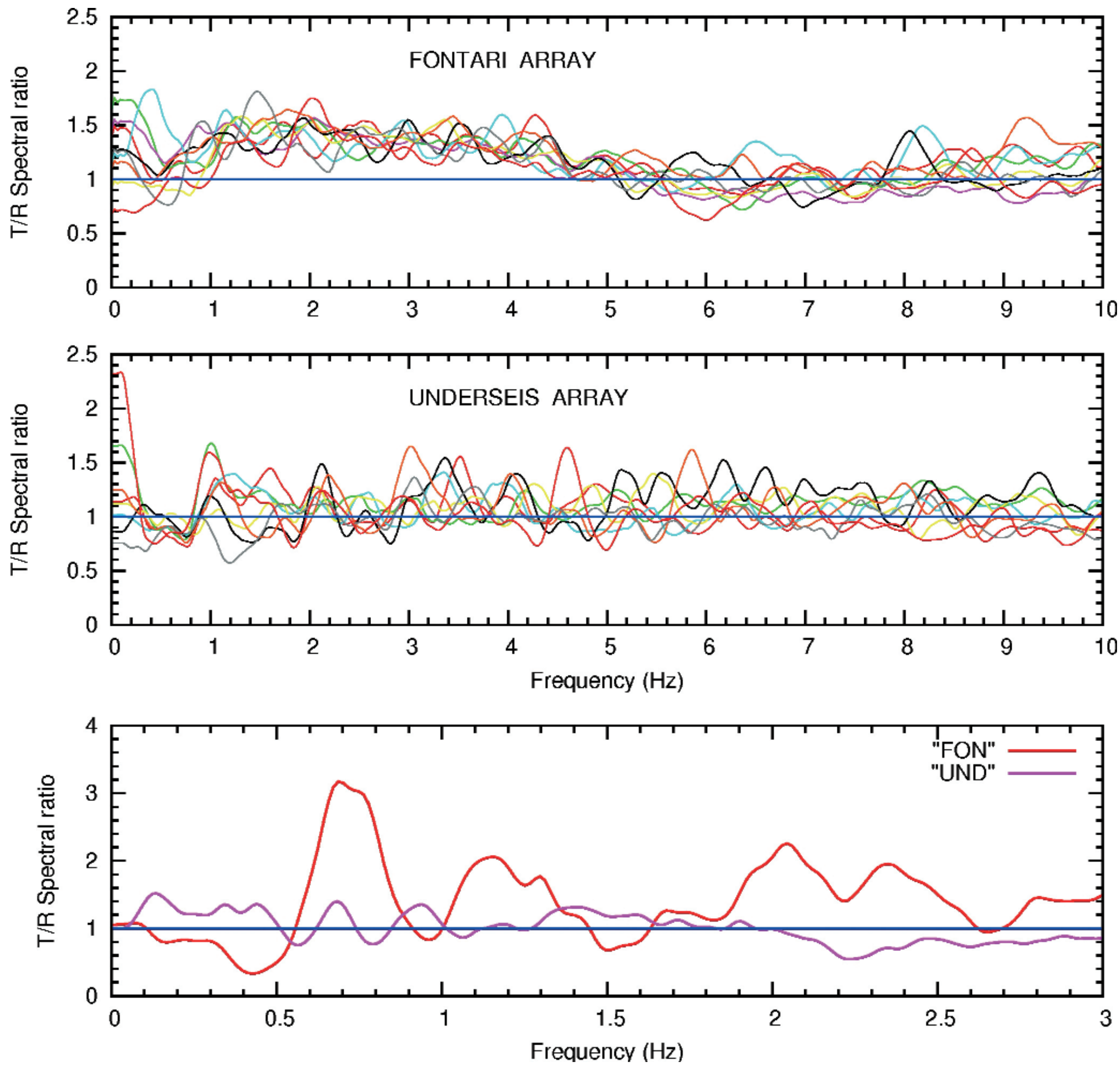

Fig. 9 - Spectral ratios between transverse and radial components for 10 regional earthquakes recorded at surface (top plot) and underground (middle plot), and for the P coda of a teleseism (bottom plot).

results are described for a tectonic environment in central Italy by Cultrera *et al*. (2003). These authors point out as the polarization of seismic noise and earthquake signals is perpendicular to the strike of seismic faults in the area. In the area of Campo Imperatore one important fault is known, located east of the array site, striking roughly E-W and then NW-SE at distance of more than 3 km, on the east sector of Mt. Gran Sasso (Galadini *et al*., 2003). Therefore, in our case a relationship between fault position and polarization of the seismic signals is not obvious. The persistence of a polarization direction measured at surface in a wide frequency range at all stations suggests that the cause of the polarization direction must involve the entire area of FON array, that is 0.6 km wide. This size, and the estimated wavelenght corresponding to the frequency band of polarized signals, support the idea that the observed polarization is produced mainly by topographic effects. Other causes, such as the presence of unconsolidated material or highly fractured rock near the stations, probably give a contribute to the polarization of the seismic wavefield. However, if this was the main contribute to the signal polarization it would require a very similar site effect among the six stations of the array, coincident with the expected topographic effect. Considering the distance of more than 0.6 km between some stations, this hypothesis seems unlikely.

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